Course/Course Code:

Data Acquisition and Microcontroller (MC-546)

Lecture # 04

SIGNAL CONDITIONING

Course Teacher:

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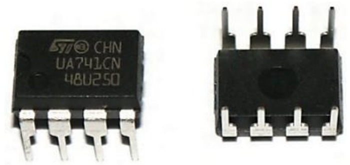
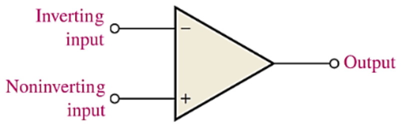
Operational Amplifiers (Op-amp IC 741)

- *Operational Amplifiers*, also known as Op-amps, are basically a voltage amplifying device.



IC Op-Amp IC 741

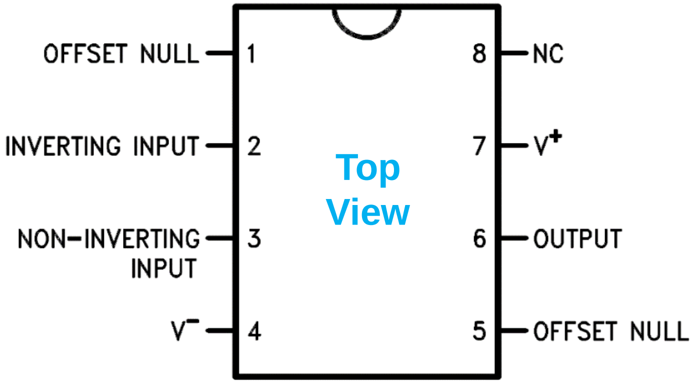
- They are essentially a core part of analog devices; to strengthen the AC-DC signals via signal conditioning and filtering.



Op-Amp Symbol

- Op-amp performs mathematical operations such as; addition, subtraction, integration and differentiation.

- They consists of two inputs (inverting and non-inverting) and one output.



Pin Configuration

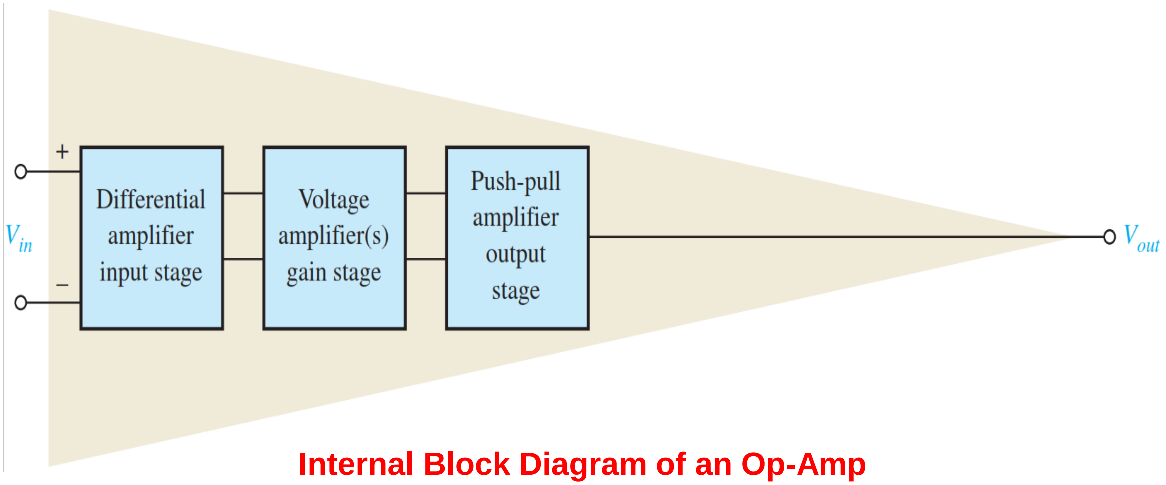
Internal Block Diagram Of An Op-amp

☐ Op-amp is typically made up of three amplifier circuits:

a) Differential amplifier-based input stage; that provides amplification of difference voltage between two inputs.

b) Voltage amplifier (class A); that provides additional gain.

c) Push-pull amplifier (class B) based output stage.


+
V_{in}
−
Differential amplifier input stage
Voltage amplifier(s) gain stage
Push-pull amplifier output stage
V_{out}

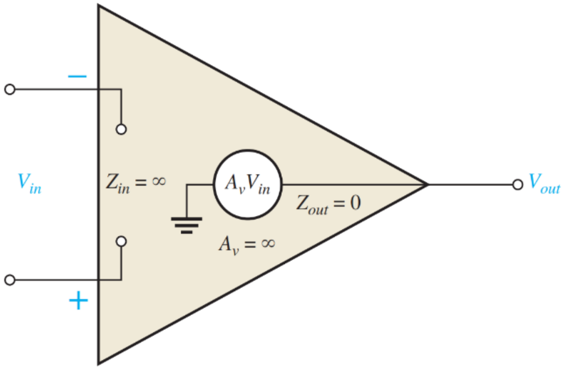
Internal Block Diagram of an Op-Amp

Op-amps Characteristics

Cont….

Ideal Op-amp Characteristics

- The ideal op-amp has infinite voltage gain, A_v and infinite bandwidth.
- It has an infinite input impedance, $Z_{in}(open)$ so that it does not load the driving source. It has a zero-output impedance, Z_{out}.
- The input voltage, V_{in}, appears between the two input terminals,
- The output voltage, V_{out}, indicated by the internal voltage source ($A_v\ V_{in}$) symbol.

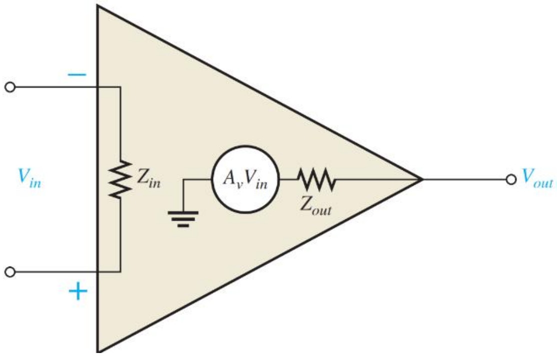


Equivalent circuit for Ideal op-amp

Op-amps Characteristics

Practical Op-amp Characteristics

- Characteristics of practical op-amps are very high voltage gain, very high input impedance, and very low output impedance.
- Another practical consideration is that there is always noise generated within the op-amp.
- **Noise** is an undesired signal that affects the quality of a desired output signal.

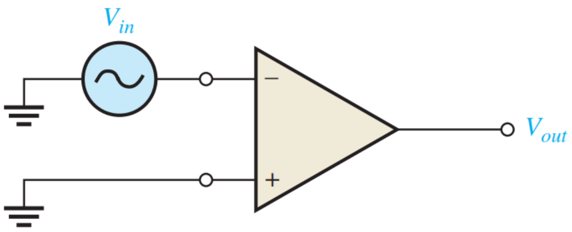


Equivalent circuit for Practical op-amp

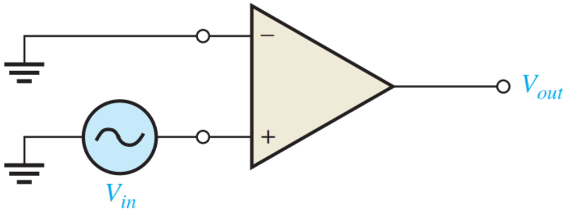
Op-amp Input Modes

Cont….

1. **Differential Mode:** The differential input mode can be classified as single-and double ended differential mode.
   - ***(a) Single-ended differential mode:*** One input is grounded, and a signal voltage is applied to the other input.

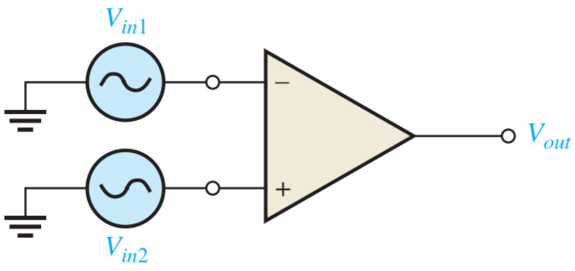


Signal voltage at inverting input results in an inverted and amplified output

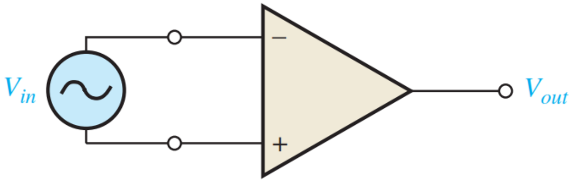


Signal voltage at non-inverting input results in a non-inverted and amplified output

   - ***(b) Double-ended differential mode:*** Two opposite-polarity (out-of-phase) signals are applied to the inverting and non-inverting inputs, respectively.



The amplified difference between the two inputs appears at the output.

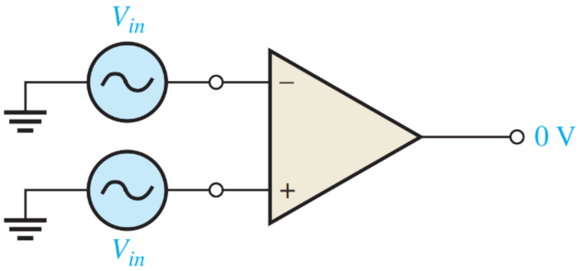


Single source connected between the two inputs

Op-amp Input Modes

2. Common Mode:

- ☐ Signal voltages of same phase, frequency, and amplitude are applied to both inputs.
- ☐ Both input tends to cancel each other, resulting in a zero-output voltage.
- ☐ Common mode is utilized to block the unwanted signal (noise) from appearing and distorting the desired output signal. This is known as common-mode rejection.



Op-amp Parameters

Cont….

Open-Loop Voltage Gain, A_{ol}

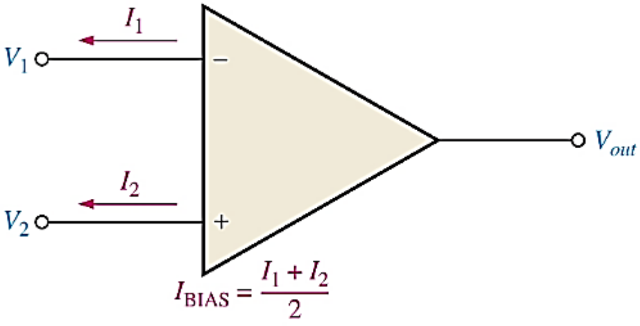
- The open-loop voltage gain, A_{ol}, of an op-amp is the internal voltage gain of the device, which represents the ratio of output voltage to input voltage when there are no external components.

Input Offset Voltage, V_{os}

- The input offset voltage, V_{os} is the differential dc voltage required between the inputs to force the output to zero volts.
- Typical values of input offset voltage are in the range of 2 mV or less.

Input Bias Current

- The input bias current is the dc current required by the inputs of the amplifier to properly operate the first stage. The input bias current is the average of both input currents and is calculated as follows:



Op-amp Parameters

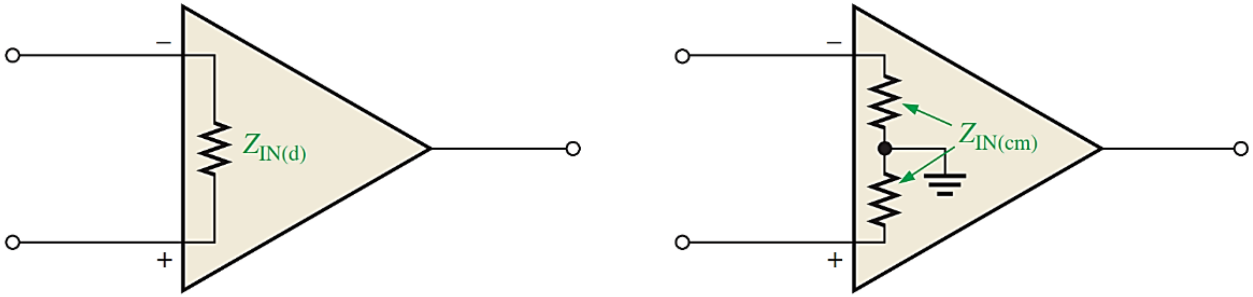
Cont….

Input Impedance:

☐ The input impedance of an op-amp can be specified as the differential and the common mode impedance.

a) The differential input impedance is the total resistance between the inverting and the non-inverting inputs.

b) The common-mode input impedance is the resistance between each input and ground.



(a) Differential input impedance (b) Common-mode input impedance

Op-amp Parameters

Cont….

Input Offset Current

- ☐ The input offset current, Ios, is the difference of the input bias currents, expressed as an absolute value:

$$Ios = |I_1 - I_2|$$

- ☐ The offset voltage developed by the input offset current is expressed as:

$$Vos = I_1 R_{in} - I_2 R_{in} = (I_1 - I_2) R_{in}$$

$$Vos = I_{OS} R_{in}$$

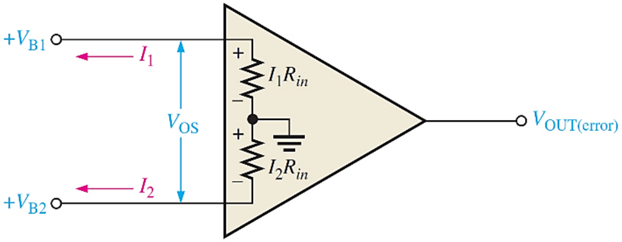
Op-amp Parameters

Cont….

Output Voltage Error

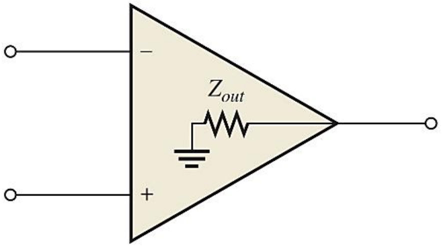
- The **error** created by I_{os} is amplified by the gain, A_v of the op-amp and appears in the output as:

$$V_{OUT(error)} = A_v I_{OS} R_{in}$$



Output Impedance

- The output impedance is the resistance viewed from the output terminal of the op-amp.



OP-AMP PARAMETERS

Cont….

Common-Mode Rejection Ratio

- ☐ The measure of an op-amp's performance in rejecting the unwanted common-mode signals is called common-mode rejection ratio, CMRR.

- ☐ CMRR is a ratio of the open-loop differential voltage gain, A_{ol}, to the common-mode gain, A_{cm}, expressed as:

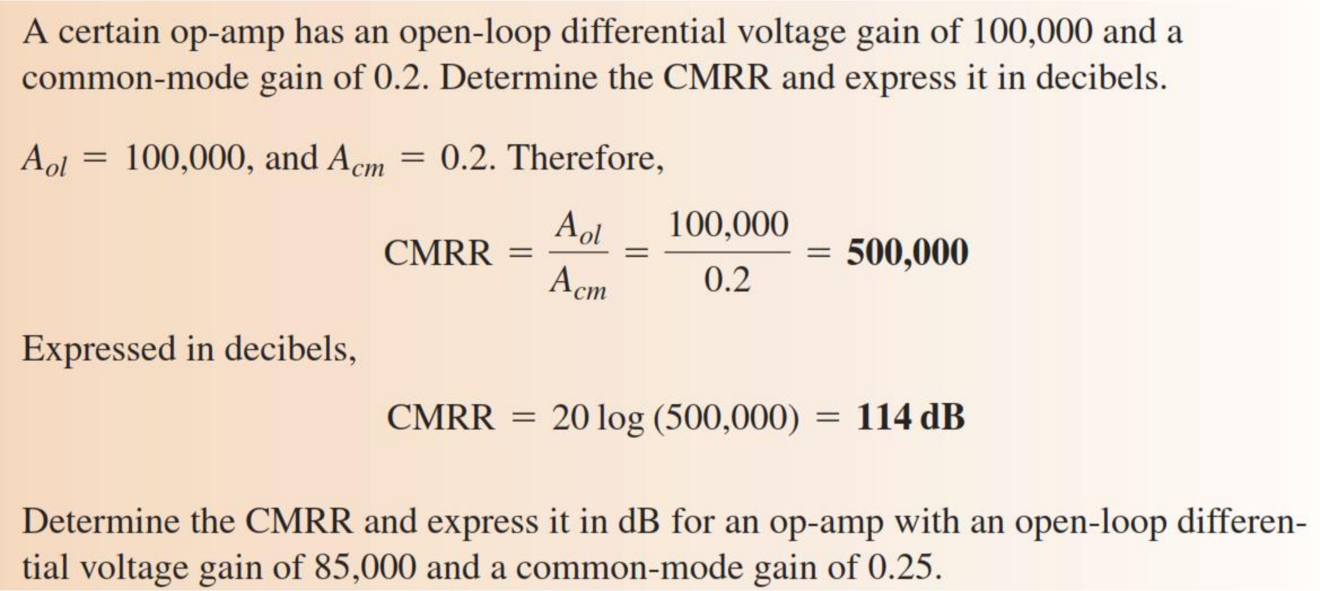
$$CMRR = \frac{A_{ol}}{A_{cm}}$$

- ☐ A very high value of CMRR means that the open-loop gain, A_{ol}, is high, while common-mode gain, A_{cm}, is low.
- ☐ The CMRR is often expressed in decibels (dB) as:

$$CMRR = 20\ log\left(\frac{A_{ol}}{A_{cm}}\right)$$

OP-AMP PARAMETERS

Cont….



Example: A certain op-amp has an open-loop differential voltage gain of 100,000 and a common-mode gain of 0.2. Determine the CMRR and express it in decibels.

Solution: $A_{ol} = 100{,}000$, and $A_{cm} = 0.2$. Therefore,

$$\text{CMRR} = \frac{A_{ol}}{A_{cm}} = \frac{100{,}000}{0.2} = \mathbf{500{,}000}$$

Expressed in decibels,

$$\text{CMRR} = 20 \log (500{,}000) = \mathbf{114\ dB}$$

Problem: Determine the CMRR and express it in dB for an op-amp with an open-loop differential voltage gain of 85,000 and a common-mode gain of 0.25.

OP-AMP PARAMETERS

Cont….

Slew Rate

- The maximum rate of change of an output voltage of an op-amp in response to a step input voltage is known as slew-rate.
- The width of the input pulse must be sufficient to allow the output to "slew" from its lower limit to its upper limit.

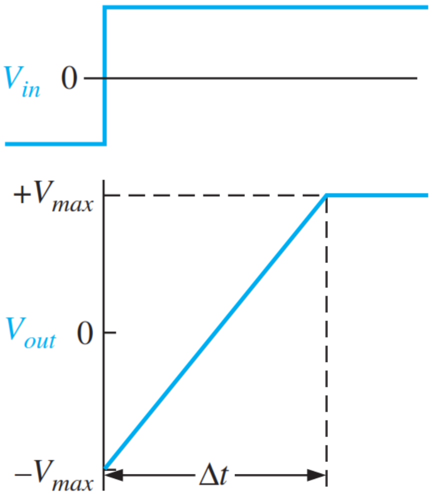
Slew Rate Measurements

- A certain time interval, Δt is required for the output voltage to go from its lower limit $-V_{max}$ to its upper limit $+V_{max}$, once the input step is applied. The slew rate is expressed as:

$$Slew\ Rate = \frac{\Delta Vout}{\Delta t}$$

- where, $\Delta V_{out} = +V_{max} - (-V_{max})$. The unit of slew rate is volts per microsecond (V/µs).

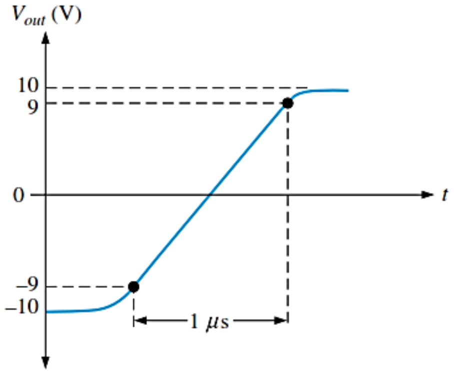
Step input voltage



Resulting output voltage

OP-AMP PARAMETERS

Example: The output voltage of a certain op-amp appears as shown in Figure in response to a step input. Determine the slew rate.



Solution: The output goes from the lower to the upper limit in 1 μs. Since this response is not ideal, the limits are taken at the 90% points, as indicated. So, the upper limit is +9 V and the lower limit is −9 V. The slew rate is

$$\text{Slew rate} = \frac{\Delta V_{out}}{\Delta t} = \frac{+9\text{ V} - (-9\text{ V})}{1\ \mu\text{s}} = \mathbf{18\ V/\mu s}$$

Problem: When a pulse is applied to an op-amp, the output voltage goes from −8 V to +7 V in 0.75 μs. What is the slew rate?

OP-AMPS WITH NEGATIVE FEEDBACK

Cont….

- Negative feedback is the process whereby a portion of the output voltage of an amplifier is returned to the input with a phase angle that opposes (or subtracts from) the input signal.

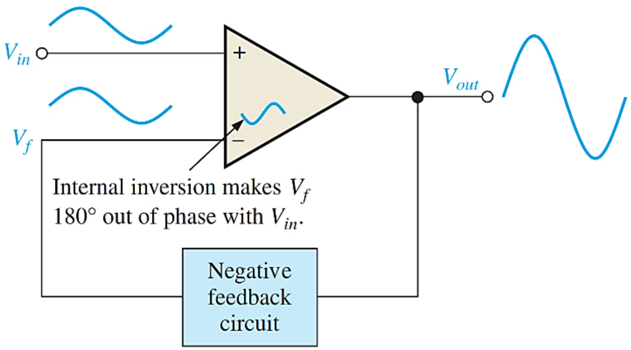

V_{in}
+
V_f
−
V_{out}
Internal inversion makes V_f 180° out of phase with V_{in}.
Negative feedback circuit

Illustration of Negative Feedback

Why Use Negative Feedback?

- Inherently, the open-loop voltage gain, A_{ol} of a typical op-amp is very high (>100,000).
- Thus, an extremely small input voltage or even offset voltage of the op-amp can drive it into saturation.

For example: Assume $V_{IN} = 1$ mV and $A_{ol} = 100{,}000$:

$$V_{OUT} = V_{IN}\,A_{ol} = (1mV)(100{,}000) = 100V$$

- Since the output level of an op-amp can never reach 100V, it is driven **deep into saturation**.
- A small input voltage drives the op-amp to its output limits, and it becomes **nonlinear.**

OP-AMPS WITH NEGATIVE FEEDBACK

Advantages of Negative Feedback:

- Negative feedback takes a portion of the output and applies it back out of phase with the input, creating an effective reduction in gain.
- An op-amp can be connected using negative feedback to stabilize the gain and increase frequency response.
- The closed loop voltage gain (A_{cl}) can be reduced and controlled so that the op-amp can function as a linear amplifier.

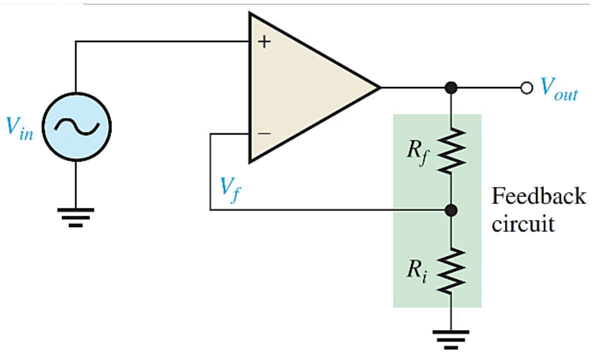
Closed-Loop Voltage Gain

- A closed-loop voltage gain, A_{cl} is the voltage gain of an op-amp with external feedback.
- The closed-loop voltage gain is determined by the external component values and can be precisely controlled by them.

NONINVERTING AMPLIFIER

Cont….

- ☐ An op-amp connected in a closed-loop configuration as a noninverting amplifier is shown in Figure.
- ☐ The input signal is applied to the noninverting (+) input.
- ☐ The output is applied back to the inverting input through the feedback circuit (closed loop) formed by the input resistor, Ri and the feedback resistor, R_f.



Noninverting Amplifier

- ☐ Resistors R_i and R_f form a voltage-divider circuit, which reduces V_{out} and connects the reduced feedback voltage, V_f to the inverting input.
- ☐ The feedback voltage is expressed as:

$$V_f = \left(\frac{R_i}{R_i + R_f}\right)V_{out}$$

NONINVERTING AMPLIFIER

Cont….

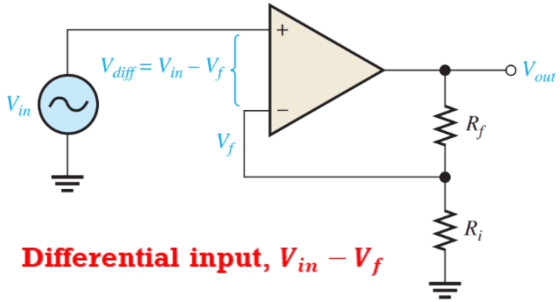
Differential Input:

- The difference of the input voltage, V_{in} and the feedback voltage, V_f is the differential input, V_{diff} to the op-amp, as shown in Figure.
- This differential voltage is amplified by the open-loop voltage gain of the op-amp (A_{ol}) and produces an output voltage expressed as:

$$V_{out} = A_{ol}(V_{in} - V_f)$$

- The loss or attenuation, B of the feedback circuit is expressed as:

$$B = \frac{R_i}{R_i + R_f}$$



Differential input, $V_{in} - V_f$

NONINVERTING AMPLIFIER

Cont….

- Substituting BV_{out} for V_f in the V_{out} equation,

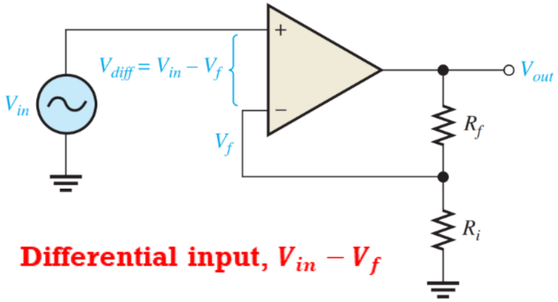
$$V_{out} = A_{ol}(V_{in} - BV_{out})$$

- Then applying the basic algebra,

$$\begin{aligned} V_{out} &= A_{ol}V_{in} - A_{ol}BV_{out} \\ V_{out} + A_{ol}BV_{out} &= A_{ol}V_{in} \\ V_{out}(1 + A_{ol}B) &= A_{ol}V_{in} \end{aligned}$$

- The overall voltage gain of the amplifier can be expressed as:

$$\frac{V_{out}}{V_{in}} = \frac{A_{ol}}{1 + A_{ol}B}$$



Differential input, $V_{in} - V_f$

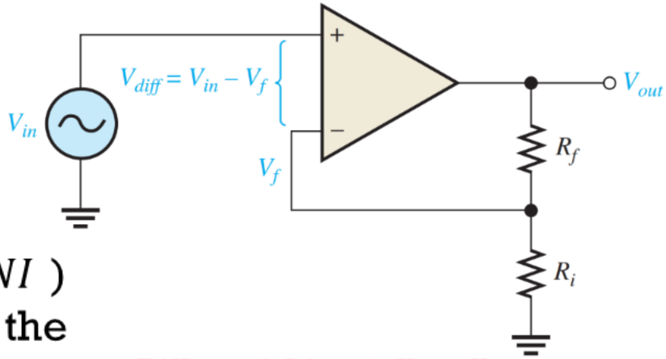
NONINVERTING AMPLIFIER

Cont….

- The product $A_{ol}B$ is typically much greater than 1, so the equation simplifies to:

$$\frac{V_{out}}{V_{in}} \cong \frac{A_{ol}}{A_{ol}B} = \frac{1}{B}$$

- The closed-loop gain of the noninverting (NI) amplifier is the reciprocal of the attenuation (B) of the feedback circuit (voltage-divider).



Differential input, $V_{in} - V_f$

$$A_{cl(\mathrm{NI})} = \frac{V_{out}}{V_{in}} \cong \frac{1}{B} = \frac{R_i + R_f}{R_i}$$

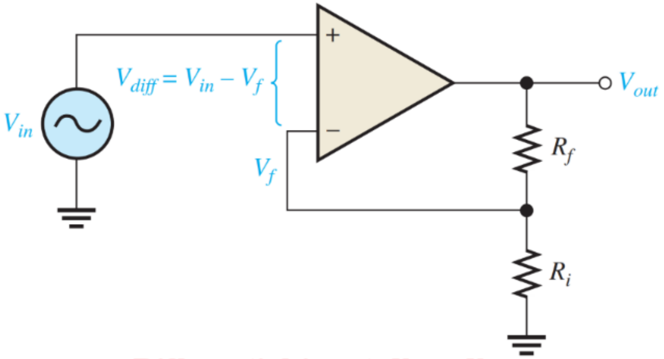
NONINVERTING AMPLIFIER

Cont….

- The product $A_{ol}B$ is typically much greater than 1, so the equation simplifies to:

- Finally,

$$\boxed{A_{cl(NI)} = 1 + \frac{R_f}{R_i}}$$



Differential input, $V_{in} - V_f$

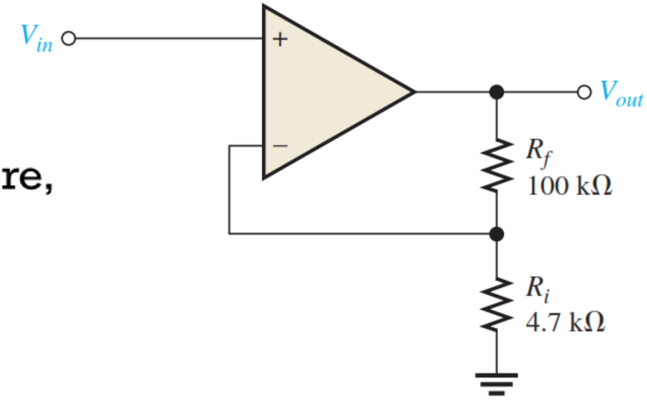
- The closed-loop gain of noninverting amplifier can be set by selecting values of R_i and R_f

NONINVERTING AMPLIFIER

Cont….

Example:

Determine the closed-loop voltage gain of the amplifier shown in the Figure.



Solution:

This is a noninverting op-amp configuration. Therefore, the closed-loop voltage gain is

$$A_{cl(NI)} = 1 + \frac{R_f}{R_i} = 1 + \frac{100\text{ k}\Omega}{4.7\text{ k}\Omega} = \mathbf{22.3}$$

Related Problem:

If R_f in the Figure is increased to 150kΩ, determine the closed-loop voltage gain.

NONINVERTING AMPLIFIER

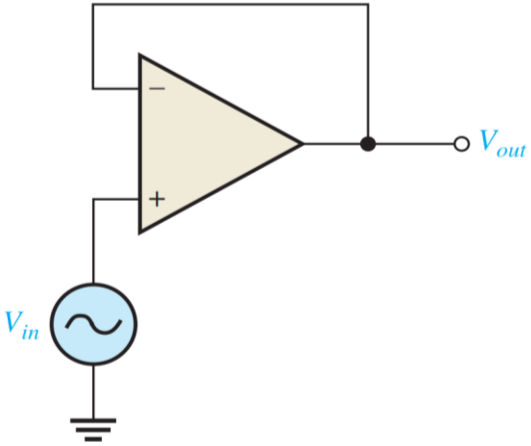
Voltage-Follower

☐ The voltage-follower configuration is a special case of the noninverting amplifier where all the output voltage is fed back to the inverting input by a straight connection.

☐ Since $B = 1$ for a voltage-follower, the closed-loop voltage of the voltage-follower is $1/B$.

☐ Hence,

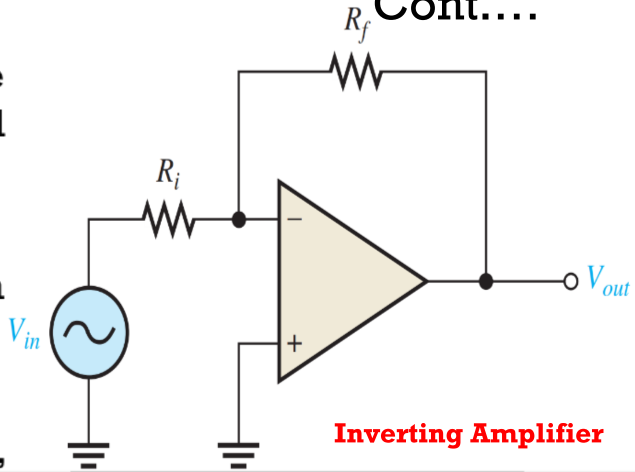
$$\boxed{A_{cl(\mathrm{VF})} = 1}$$



Op-amp voltage-follower

INVERTING AMPLIFIER

Cont….



Inverting Amplifier

- The voltage-follower configuration is a special case of the noninverting amplifier where all the output voltage is fed back to the inverting input by a straight connection.
- For inverting amplifier, the input signal is applied through a series input resistor, R_i to the inverting input.
- Also, the output is fed back through Rf to the same input, while the noninverting (+) input is grounded.
- For an inverting amplifier, the infinite input impedance implies zero current at the inverting input i.e., no voltage drop between the inverting and noninverting inputs.
- Moreover, the voltage at the inverting input is zero because the noninverting (+) input is grounded.
- This zero voltage at the inverting input terminal is referred to as ‘virtual ground’.

INVERTING AMPLIFIER

Cont….

- Since there is no current at the inverting input, the current through R_i and the current through R_f are equal.

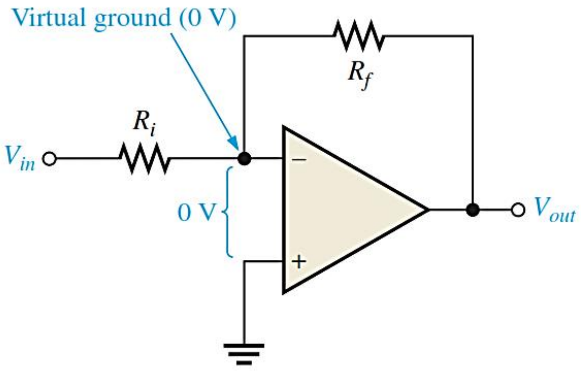
$$I_{in} = I_f$$

- The voltage across R_i equals V_{in} because the resistor is connected to virtual ground at the inverting input of the op-amp. Therefore,

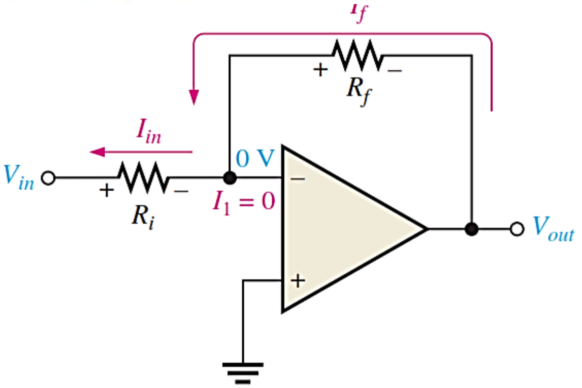
$$I_{in} = \frac{V_{in}}{R_i}$$

- Also, the voltage across R_f equals $-V_{out}$ because of virtual ground, and therefore,

$$I_f = \frac{-V_{out}}{R_f}$$



(a) Virtual ground



(b) $I_{in} = I_f$ and current at the inverting input (I_1) is 0.

INVERTING AMPLIFIER

Cont….

- Since $I_f = I_{in}$,

$$\frac{-V_{out}}{R_f} = \frac{V_{in}}{R_i}$$

- Rearranging the terms,

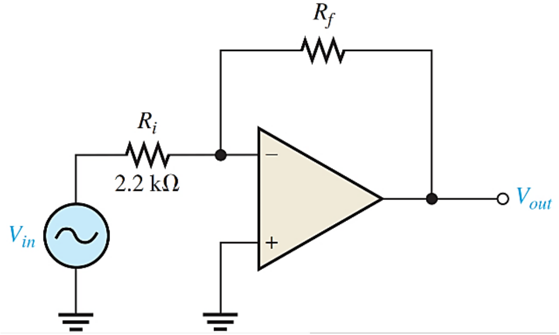
$$\frac{V_{out}}{V_{in}} = -\frac{R_f}{R_i}$$

- Finally, V_{out}/V_{in} is the overall gain of the inverting (I) amplifier.

$$\boldsymbol{A_{cl(\mathrm{I})} = -\frac{R_f}{R_i}}$$

INVERTING AMPLIFIER

Example: Given the op-amp configuration in Figure, determine the value of R_f required to produce a closed-loop voltage gain of -100.



Solution: Knowing that $R_i = 2.2k\Omega$ and the absolute value of the closed-loop gain is $|A_{cl(I)}| = 100$, the value of R_f can be calculated as follows:

$$|A_{cl(\mathrm{I})}| = \frac{R_f}{R_i}$$

$$R_f = |A_{cl(\mathrm{I})}|R_i = (100)(2.2\,\mathrm{k\Omega}) = \mathbf{220\,k\Omega}$$

Related Problem:

If R_i is changed to 2.7 kΩ in Figure, what value of R_f is required to produce a closed-loop gain with an absolute value of 25?

COMPARATORS

- Although op-amps are much slower and lack other special features, they have **very high open-loop gain**, which enables them to *detect very tiny differences in the inputs*.

- A **comparator** is a specialized op-amp circuit that *compares the two input voltages* and produces an output that is always at either one of two states, **indicating the greater or less** than relationship between the inputs.

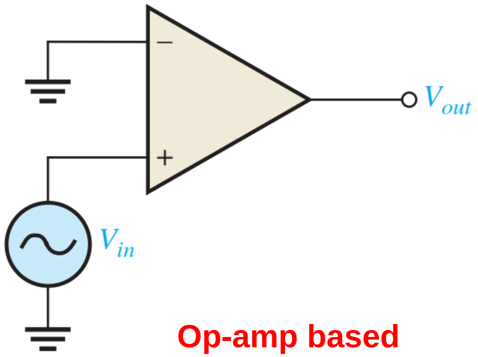
- In this application, the op-amp is *used without negative feedback* (open-loop) configuration, with the input voltage on one input and a reference voltage on the other.

- In general, comparators cannot be used as op-amps, but an op-amp without negative feedback is essentially a comparator in noncritical applications.

ZERO-LEVEL DETECTION

Cont….

- ☐ The application of an op-amp used as a comparator is to determine when an input voltage exceeds a certain level.
- ☐ A zero-level detector is shown in Figure.

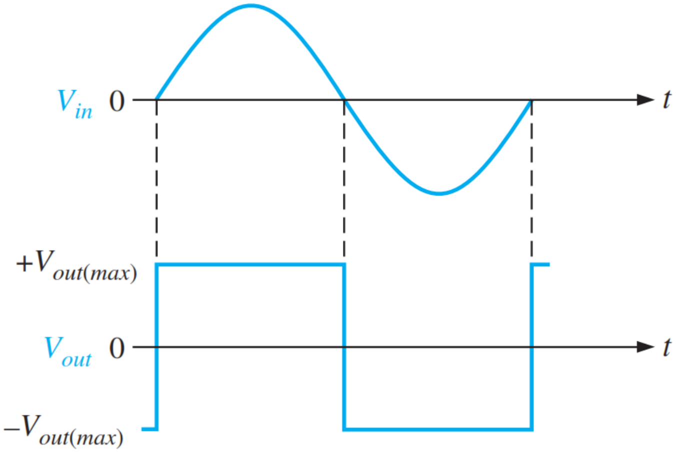


Op-amp based zero-level detector circuit

- ☐ Notice that the inverting input is grounded to produce a zero level and that the input signal voltage is applied to the noninverting input.
- ☐ Because of the high open-loop voltage gain, a very small difference voltage between the two inputs drives the amplifier into saturation, causing the output voltage to go to its limit.
- ☐ For example, consider an op-amp having $A_{ol} = 100{,}000$. A voltage difference of only 0.25 mV between the inputs could produce an output voltage of (0.25mV)(100,000). i.e., 25 V.

ZERO-LEVEL DETECTION

- ☐ However, since most op-amps have maximum output voltage limitations near the value of their dc supply voltages (±13 V or ±15 V), the device would be driven into saturation.
- ☐ The result of a sinusoidal input voltage applied to the noninverting input of the zero-level detector.
- ☐ When the sine wave is positive, the output is at its maximum positive level, as shown in Figure.
- ☐ When the sine wave crosses 0, the amplifier is driven to its opposite state and the output goes to its maximum negative level, as shown in Figure.
- ☐ The zero-level detector can be used as a squaring circuit to produce a square wave from a sine wave.



Input-output waveforms for Op-amp based zero-level detector circuit

NON-ZERO LEVEL DETECTION

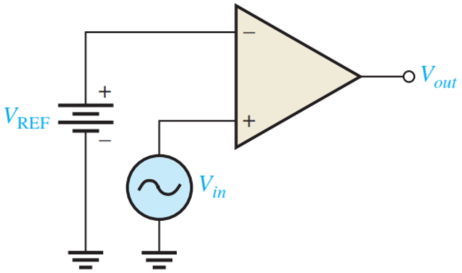
Cont….

- The zero-level detector can be modified to detect positive and negative voltages by connecting a fixed reference voltage source to the inverting input, as shown in Figure (a).

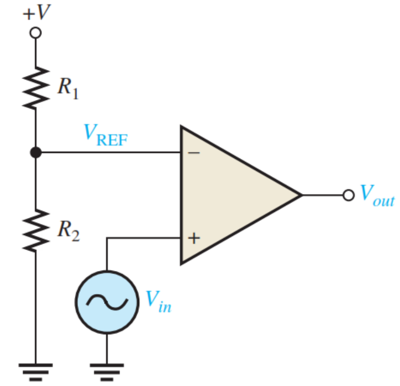
- A more practical arrangement is shown in Figure (b) using a voltage divider to set the reference voltage, V_{REF}, as follows:

$$V_{REF} = \frac{R_2}{R_1 + R_2}(+V)$$

- where $+V$ is the positive DC supply voltage of op-amp.



(a) Battery reference

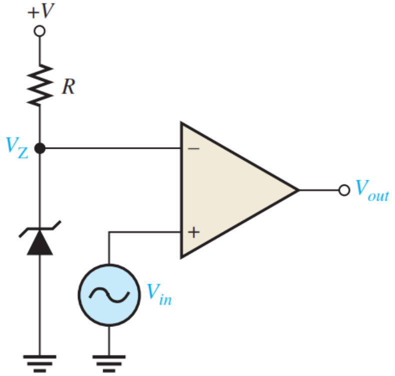


(b) Voltage-divider reference

NON-ZERO-LEVEL DETECTION

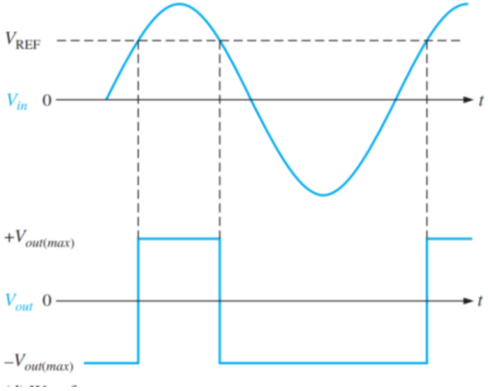
Cont….

- The circuit in Figure (c) uses a Zener diode to set the reference voltage ($V_{REF} = V_Z$). As long as V_{in} is less than V_{REF}, the output remains at the maximum negative level.



(c) Zener diode sets reference voltage

- When the sinusoidal input voltage exceeds the reference voltage, the output goes to its maximum positive voltage, as shown in the Figure (d).



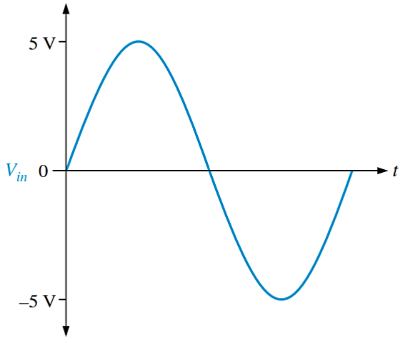
(d) Waveforms

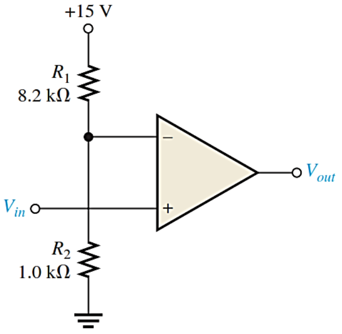
NON-ZERO-LEVEL DETECTION

Cont….

Example:

The input signal is applied to the comparator as shown in the Figure. Draw the output showing its proper relationship to the input signal. Assume the maximum output levels of the comparator are ±14 V.





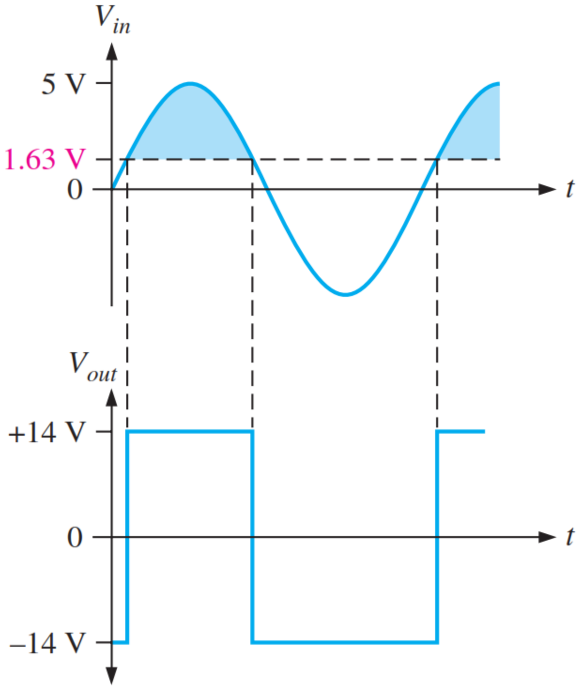
Solution:

The reference voltage is set by R_1 and R_2 as follows:

$$V_{\mathrm{REF}} = \frac{R_2}{R_1 + R_2}(+V) = \frac{1.0\,\mathrm{k}\Omega}{8.2\,\mathrm{k}\Omega + 1.0\,\mathrm{k}\Omega}(+15\ \mathrm{V}) = 1.63\ \mathrm{V}$$

NON-ZERO-LEVEL DETECTION

- ☐ As shown in Figure, each time the input exceeds +1.63 V, the output voltage switches to its +14 V level, and each time the input goes below +1.63 V, the output switches back to its –14 V level.



Related Problem:

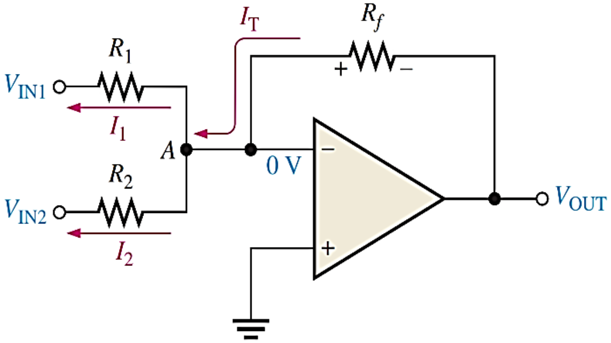
Determine the reference voltage in Figure (slide 10), if $R_1 = 22\ k\Omega$ and $R_2 = 3.3\ k\Omega$.

SUMMING AMPLIFIER WITH UNITY GAIN

Cont….

- A summing amplifier has two or more inputs, and its output voltage is proportional to the negative of the algebraic sum of its input voltages.

- A two-input summing amplifier is shown in next slide, but any number of inputs can be used. The operation of the circuit and derivation of the output expression are as follows.



Two-input inverting summing amplifier

- Two voltages, V_{IN1} and V_{IN2}, are applied to the inputs and produce currents I_1 and I_2, as shown in Figure.

- Using the concepts of infinite input impedance and virtual ground, you can determine that the inverting input of the op-amp is approximately 0 V and has no current through it.

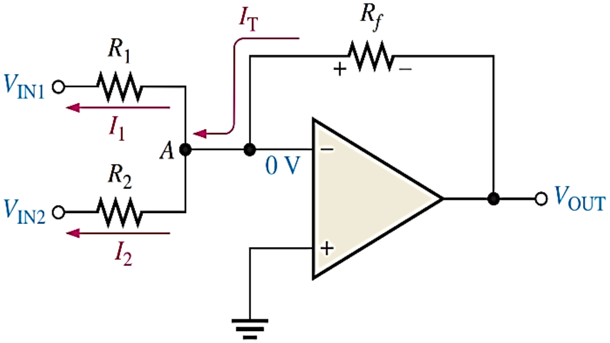
SUMMING AMPLIFIER WITH UNITY GAIN

- This means that the total current I_T, which goes through R_f divides into I_1 and I_2 at summing point A, as indicated in Figure.

- Two voltages, V_{IN1} and V_{IN2}, are applied to the inputs and produce currents $I_1$and I_2, as shown in Figure.

- Using the concepts of infinite input impedance and virtual ground, you can determine that the inverting input of the op-amp is approximately 0 V and has no current through it.

- This means that the total current I_T, which goes through R_f divides into I_1 and I_2 at summing point A, as indicated in Figure.



Two-input inverting summing amplifier

SUMMING AMPLIFIER WITH GAIN GREATER THAN UNITY Cont….

- When R_f is larger than the input resistors, the amplifier has a gain of R_f/R, where R is the value of each equal-value input resistor.

- The general expression for the output voltage is

$$V_{\mathrm{OUT}} = -\frac{R_f}{R}(V_{\mathrm{IN1}} + V_{\mathrm{IN2}} + \cdots + V_{\mathrm{IN}n})$$

- As you can see, the output voltage has the same magnitude as the sum of all the input voltages multiplied by a constant determined by the ratio $-(R_f/R)$.

SUMMING AMPLIFIER WITH GAIN GREATER THAN UNITY

Example: Determine the output voltage for the summing amplifier in Figure.

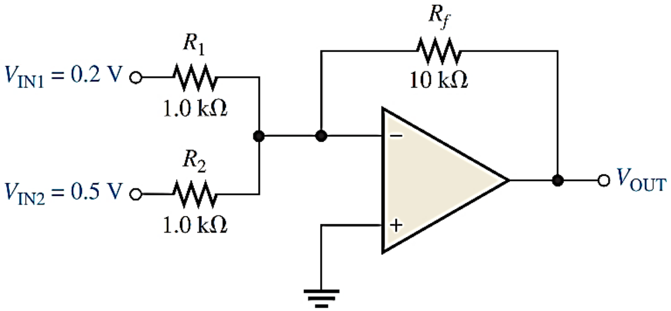
Solution:

$$R_f = 10\,\text{k}\Omega \text{ and } R = R_1 = R_2 = 1.0\,\text{k}\Omega.$$

$$V_{\text{OUT}} = -\frac{R_f}{R}(V_{\text{IN1}} + V_{\text{IN2}})$$

$$= -\frac{10\,\text{k}\Omega}{1.0\,\text{k}\Omega}(0.2\,\text{V} + 0.5\,\text{V})$$

$$= -10(0.7\,\text{V}) = \mathbf{-7\,V}$$



Related Problem:

Determine the output voltage in Figure if the two input resistors are 2.2 kΩ and the feedback resistor is 18 kΩ.

AVERAGING AMPLIFIER

Cont….

- As we know that the average of several numbers is taken by first adding the numbers and then dividing by the quantity of numbers.

- A summing amplifier can be made to produce the mathematical average of the input voltages, following the relation.

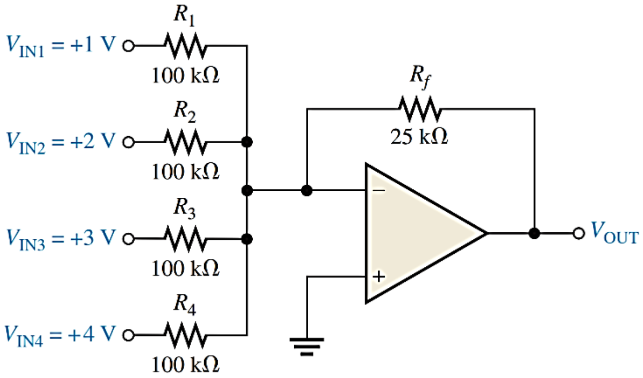
$$V_{\mathrm{OUT}} = -\frac{R_f}{R}(V_{\mathrm{IN1}} + V_{\mathrm{IN2}} + \cdots + V_{\mathrm{IN}n})$$

- This is done by setting the ratio Rf/R equal to the reciprocal of the number of inputs (n).

AVERAGING AMPLIFIER

Cont….

Example: Show that the amplifier in Figure produces an output whose magnitude is the mathematical average of the input voltages.



Solution:

Since the input resistors are equal, R = 100 kΩ . The output voltage is

$$V_{OUT} = -\frac{R_f}{R}(V_{IN1} + V_{IN2} + V_{IN3} + V_{IN4})$$

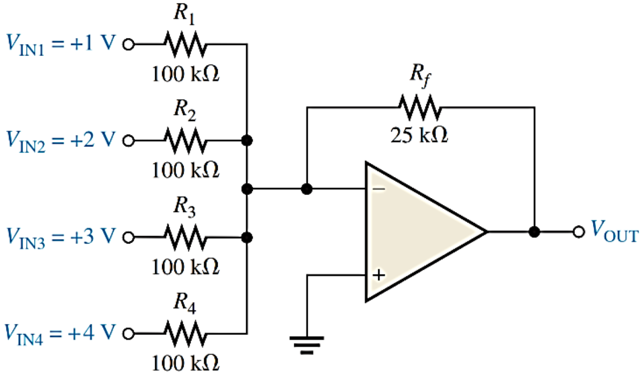
$$= -\frac{25\text{ k}\Omega}{100\text{ k}\Omega}(1\text{ V} + 2\text{ V} + 3\text{ V} + 4\text{ V})$$

$$= -\frac{1}{4}(10\text{ V}) = \mathbf{-2.5\text{ V}}$$

AVERAGING AMPLIFIER

A simple calculation shows that the average of the input values is the same magnitude as V_{OUT} but of opposite sign.

$$V_{\mathrm{IN(avg)}} = \frac{1\ \mathrm{V} + 2\ \mathrm{V} + 3\ \mathrm{V} + 4\ \mathrm{V}}{4} = \frac{10\ \mathrm{V}}{4} = 2.5\ \mathrm{V}$$



Related Problem:

Specify the changes required in the averaging amplifier in Figure in order to handle five inputs.

SCALING ADDER

Cont….

- ☐ A different weight can be assigned to each input of a summing amplifier by simply adjusting the values of the input resistors. The output voltage can be expressed as

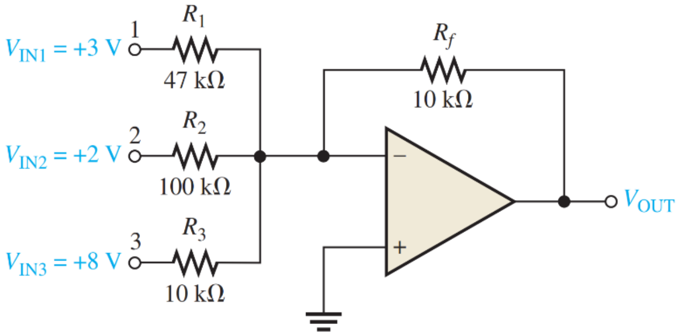
$$V_{OUT} = -\left(\frac{R_f}{R_1}V_{IN1} + \frac{R_f}{R_2}V_{IN2} + \cdots + \frac{R_f}{R_n}V_{INn}\right)$$

- ☐ The weight of an input is set by the ratio of R_f to the resistance, R_x, for that input ($R_x = R_1, R_2, \ldots R_n$).

- ☐ **For example**, if an input voltage is to have a weight of 1, then $R_x = R_f$. Or, if a weight of 0.5 is required, $R_x = 2R_f$.

SCALING ADDER

Example: Determine the weight of each input voltage for the scaling adder in Figure and find the output voltage.



Solution:

$$\text{Weight of input 1: } \frac{R_f}{R_1} = \frac{10\,\text{k}\Omega}{47\,\text{k}\Omega} = \mathbf{0.213}$$

$$\text{Weight of input 2: } \frac{R_f}{R_2} = \frac{10\,\text{k}\Omega}{100\,\text{k}\Omega} = \mathbf{0.100}$$

$$\text{Weight of input 3: } \frac{R_f}{R_3} = \frac{10\,\text{k}\Omega}{10\,\text{k}\Omega} = \mathbf{1.00}$$

Using the formula for the output voltage

$$V_{OUT} = -\left(\frac{R_f}{R_1}V_{IN1} + \frac{R_f}{R_2}V_{IN2} + \frac{R_f}{R_3}V_{IN3}\right)$$

$$= -[0.213(3\text{ V}) + 0.100(2\text{ V}) + 1.00(8\text{ V})]$$

$$= -(0.639\text{ V} + 0.2\text{ V} + 8\text{ V}) = \mathbf{-8.84\text{ V}}$$

Related Problem:

a) Determine the weight of each input voltage in Figure if $R_1 = 22$ kΩ, $R_2 = 82$ kΩ, $R_3 = 56$ kΩ and $R_f = 10$ kΩ.

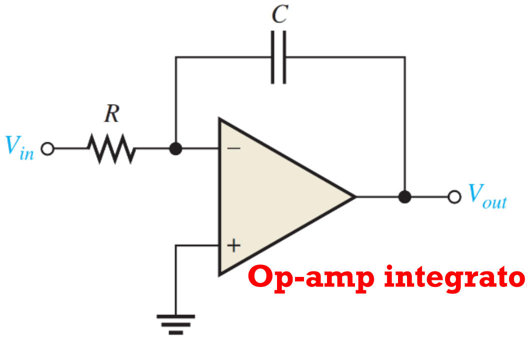
b) Also find V_{OUT}.

THE OP-AMP INTEGRATOR

Cont….

The Ideal Integrator

- ☐ An ideal integrator is shown in Figure.
- ☐ Notice that the feedback element is a capacitor that forms an RC circuit with the input resistor.



Op-amp integrator

How a Capacitor Charges?

To understand how an integrator works, it is important to review how a capacitor charges.

Recall that the charge Q on a capacitor is proportional to the charging current (I_c) and the time (t).

$$Q = I_c t$$

Also, in terms of the voltage, the charge on a capacitor is

$$Q = CV_C$$

THE OP-AMP INTEGRATOR

Cont….

- From these two relationships, the capacitor voltage can be expressed as

$$V_c = \left(\frac{I_c}{C}\right)t$$

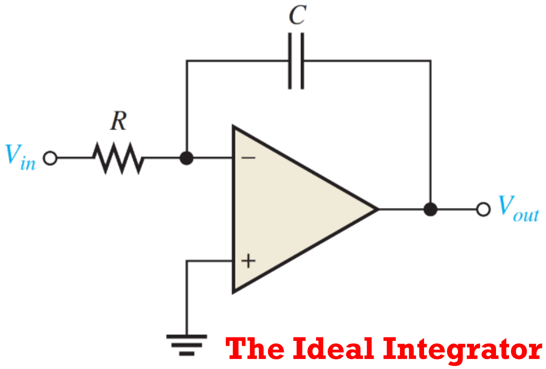
- This expression has the form of an equation for a straight line that begins at zero with a constant slope of I_c/C.
- Remember from algebra that the general formula for a straight line is $y = mx + b$.
- In this case, $y = V_c, m = I_c/C, x = t,$ and $b = 0$.
- Recall that the capacitor voltage in a simple *RC* circuit is not linear but is exponential

THE OP-AMP INTEGRATOR

Cont….

- ☐ Thus, producing a straight-line (linear) voltage rather than an exponential voltage.
- ☐ Recall that the charge Q on a capacitor is proportional to the charging current (I_c) and the time (t).

$$Q = I_c t$$



The Ideal Integrator

- ☐ Also, in terms of the voltage, the charge on a capacitor is; $Q = CV_C$
- ☐ From relationships, the capacitor voltage can be expressed as;

$$V_c = \left(\frac{I_c}{C}\right)t$$

THE OP-AMP INTEGRATOR

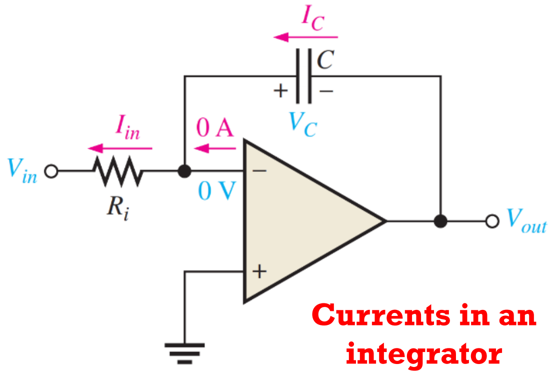
Cont….

- In Figure, the inverting input of the op-amp is at virtual ground (0 V), so the voltage across R_i equals V_{in}. Therefore, the input current is

$$I_{in} = \frac{V_{in}}{R_i}$$

- If V_{in} is a constant voltage, then I_{in} is also a constant because the inverting input always remains at 0 V, keeping a constant voltage across R_i .
- Because of the very high input impedance of the op-amp, there is negligible current at the inverting input.
- This makes all the input current go through the capacitor, as indicated in Figure.

$$I_c = I_{in}$$



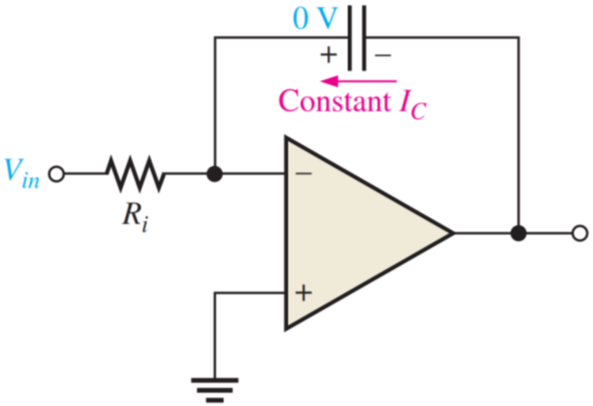
Currents in an integrator

THE OP-AMP INTEGRATOR

Cont….

The Capacitor Voltage:

- Since I_{in} is constant, so is I_c. The constant I_c charges the capacitor linearly and produces a linear voltage across C.
- The positive side of the capacitor is held at 0 V by the virtual ground of the op-amp.
- The voltage on the negative side of the capacitor, which is the op-amp output voltage, decreases linearly from zero as the capacitor charges, as shown in Figure.
- This voltage, V_C, is called a negative ramp and is then consequence of a constant positive input.



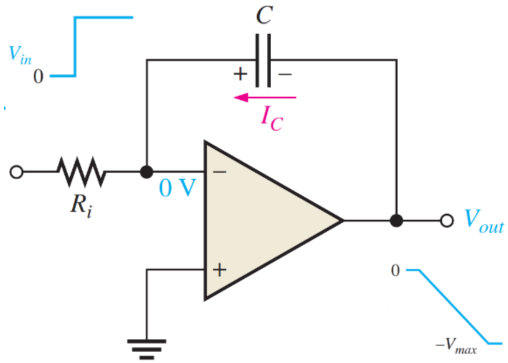
A linear ramp voltage is produced across the capacitor by the constant charging current.

THE OP-AMP INTEGRATOR

Cont….

The Output Voltage:

- V_{out} is the same as the voltage on the negative side of the capacitor.
- When a constant positive input voltage in the form of a step or pulse (a pulse has a constant amplitude when high) is applied, the output ramp decreases negatively until the op-amp saturates at its maximum negative level, as indicated in Figure.



A constant input voltage produces a ramp on the output of the integrator

Rate of Change of the Output Voltage:

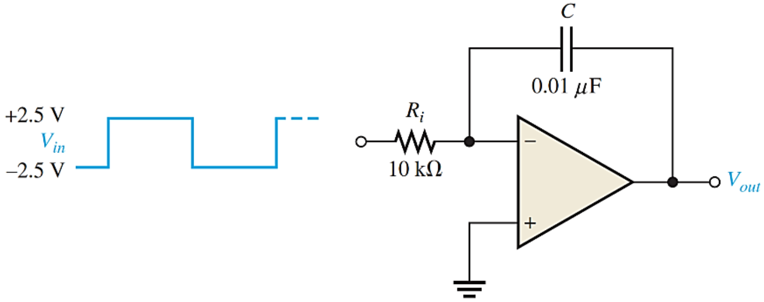
- The rate at which the capacitor charges, and therefore the slope of the output ramp, is set by the ratio I_c/C, as you have seen.
- Since $I_c = V_{in}/R_i$, the rate of change or slope of the integrator's output voltage is $\Delta V_{out}/\Delta t$.

$$\frac{\Delta V_{out}}{\Delta t} = -\frac{V_{in}}{R_i C}$$

THE OP-AMP INTEGRATOR

Cont….

Example: (a) Determine the rate of change of the output voltage in response to the input square wave, as shown for the ideal integrator in Figure. The output voltage is initially zero. The pulse width is 100 μs. (b) Describe the output and draw the waveform.



Solution:

(a) The rate of change of the output voltage during the time that the input is at +2.5 V (capacitor charging) is

$$\frac{\Delta V_{out}}{\Delta t} = -\frac{V_{in}}{R_iC} = -\frac{2.5\,\text{V}}{(10\,\text{k}\Omega)(0.01\,\mu\text{F})}$$

$$= -25\,\text{kV/s} = \mathbf{-25\,mV/\mu s}$$

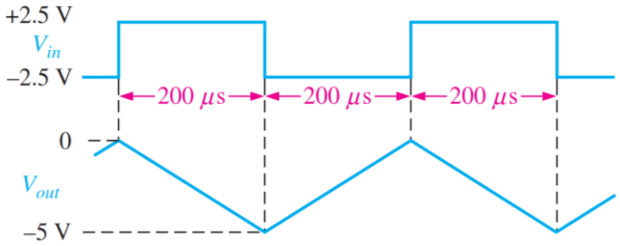
The rate of change of the output during the time that the input is negative (capacitor discharging) is the same as during charging except it is positive.

$$\frac{\Delta V_{out}}{\Delta t} = +\frac{V_{in}}{R_iC} = \mathbf{+25\,mV/\mu s}$$

THE OP-AMP INTEGRATOR

Cont…

(b) When the input is at +2.5 V, the output is a negative-going ramp. When the input is at –2.5 V the output is a positive-going ramp.



$$\Delta V_{out} = (25\ \text{mV}/\mu\text{s})(200\ \mu\text{s}) = 5\ \text{V}$$

During the time, the input is at +2.5 V, the output will go from 0 to –5 V. During the time, the input is at –2.5 V, the output will go from –5 V to 0 V. Therefore, the output is a triangular wave with peaks at 0 V and –5 V, as shown in Figure.

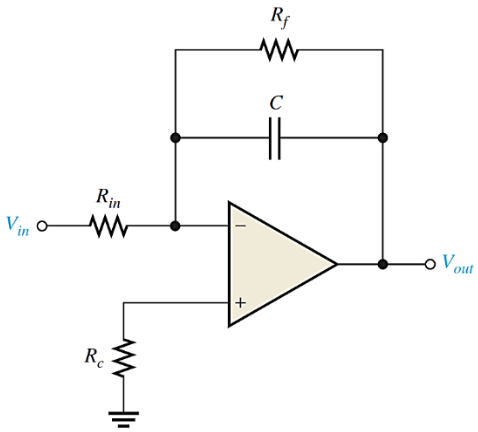
Related Problem:

Modify the integrator in Figure to make the output change from 0 to –5 V in 100 *μ*s with the same input.

THE OP-AMP INTEGRATOR

Cont….

The Practical Integrator:



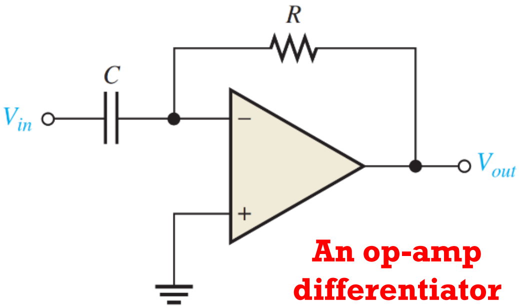
- ☐ In a **practical integrator**, any dc error voltage due to offset error will cause the output to produce a ramp that moves toward either positive or negative saturation (depending on the offset), even when no signal is present.
- ☐ Various solutions are available, such as chopper stabilized amplifiers; however, the simplest solution is to use a resistor in parallel with the capacitor in the feedback path, as shown in Figure.
- ☐ The feedback resistor, R_f, should be large compared to the input resistor R_{in}, in order to have a negligible effect on the output waveform.
- ☐ In addition, a compensating resistor, R_C , may be added to the noninverting input to balance the effects of bias current.

THE OP-AMP DIFFERENTIATOR

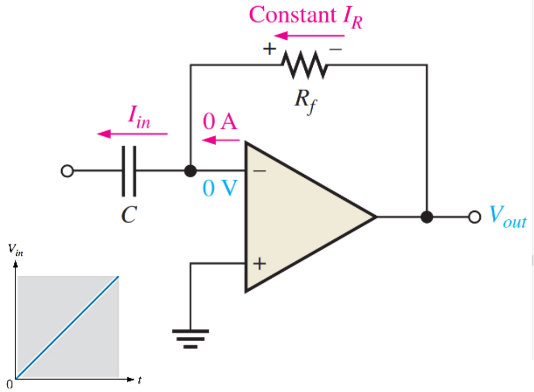
Cont….

The Ideal Differentiator:

- ☐ An ideal differentiator is shown in Figure. Notice how the placement of the capacitor and resistor differ from the integrator. The capacitor is now the input element, and the resistor is the feedback element.
- ☐ A differentiator produces an output that is proportional to the rate of change of the input voltage.
- ☐ To see how the differentiator works, apply a positive-going ramp voltage to the input as indicated in Figure.
- ☐ In this case, $I_C = I_{in}$ and the voltage across the



An op-amp differentiator



THE OP-AMP DIFFERENTIATOR

Cont….

- ☐ From the basic formula, $V_c = (I_c/C)t$, *the capacitor current is*

$$I_c = \left(\frac{V_c}{t}\right)C$$

- ☐ Since the current at the inverting input is negligible, $I_R = I_c$. Both currents are constant because the slope of the capacitor voltage (V_C/t) *is constant.*
- ☐ The output voltage is also constant and equal to the voltage across Rf because one side of the feedback resistor is always 0 V (virtual ground).

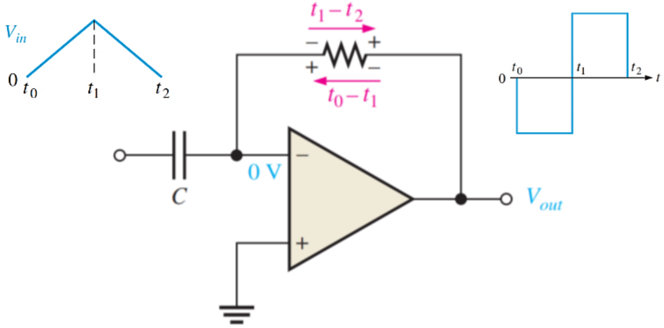
$$V_{out} = I_R R_f = I_C R_f$$

$$V_{out} = -\left(\frac{V_C}{t}\right)R_f C$$

THE OP-AMP DIFFERENTIATOR

Cont….

- The output voltage is proportional to the slope (rate of change) of the input. The constant of proportionality is the time constant, $R_f C$.
- The output is negative when the input is a positive-going ramp and positive when the input is a negative-going ramp, as illustrated in Figure (next slide).
- During the positive slope of the input, the capacitor is charging from the input source and the constant current through the feedback resistor is in the direction shown.

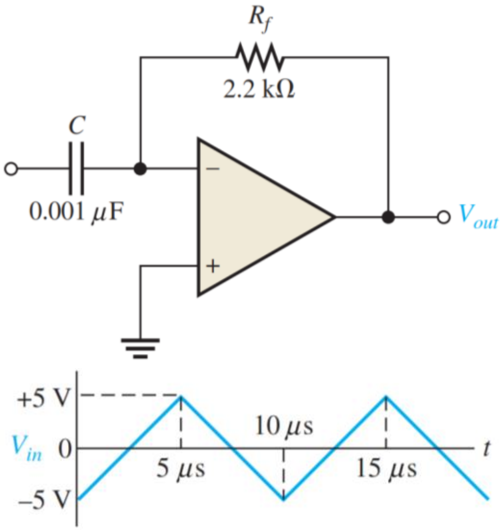


Output of a differentiator with a series of positive and negative ramps (triangle wave) on the input

THE OP-AMP DIFFERENTIATOR

Cont….

Example: Determine the output voltage of the ideal op-amp differentiator in Figure for the triangular-wave input shown.



Solution: Starting at $t = 0$, the input voltage is a positive-going ramp ranging from –5 V to +5 V (a +10 V change) in 5 µs. Then it changes to a negative-going ramp ranging from +5 V to –5 V (a –10 V change) in 5 µs.

$$R_f C = (2.2\ \text{k}\Omega)(0.001\ \mu\text{F}) = 2.2\ \mu\text{s}$$

First, need to determine the slope or rate of change (V_C/t) of the positive-going ramp and than calculate the output voltage as follows:

$$\frac{V_C}{t} = \frac{10\ \text{V}}{5\ \mu\text{s}} = 2\ \text{V}/\mu\text{s}$$

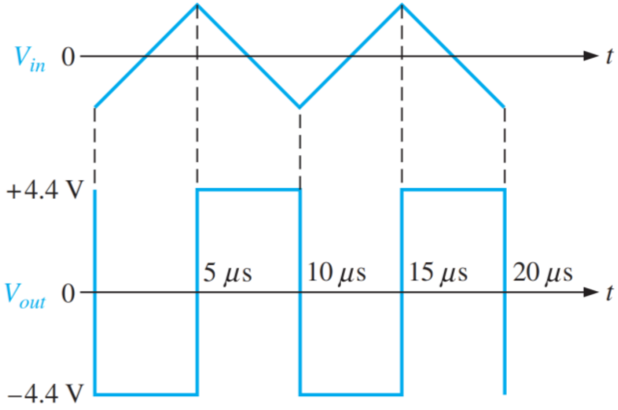
THE OP-AMP DIFFERENTIATOR

Cont….

$$V_{out} = -\left(\frac{V_C}{t}\right)R_f C = -(2\text{ V}/\mu\text{s})2.2\ \mu\text{s} = \mathbf{-4.4\ V}$$

Likewise, the slope of the negative-going ramp is –2 V/μs, and the output voltage is

$$V_{out} = -(-2\text{ V}/\mu\text{s})2.2\ \mu\text{s} = \mathbf{+4.4\ V}$$



Graph of the output voltage waveform relative to the input

Related Problem:

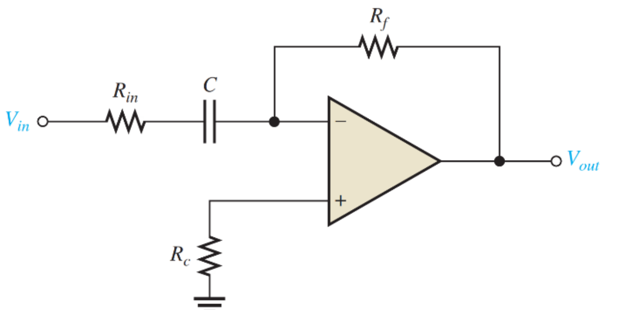
What would the output voltage be if the feedback resistor in Figure is changed to 3.3 kΩ?

THE OP-AMP DIFFERENTIATOR

Cont….

The Practical Differentiator:

- The ideal differentiator uses a capacitor in series with the inverting input. Because a capacitor has very low impedance at high frequencies, the combination of R_f and C form a very high gain amplifier at high frequencies. This means that a differentiator circuit tends to be noisy because electrical noise mainly consists of high frequencies.

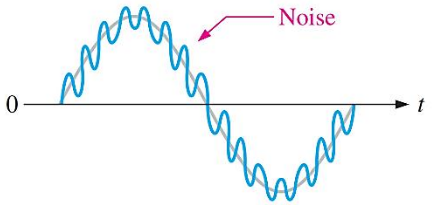


Practical differentiator

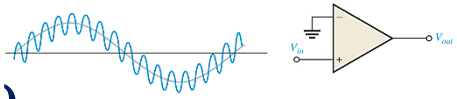
- The solution to this problem is simply to add a resistor, R_{in}, in series with the capacitor to form practical differentiator shown in Figure, which acts as a low-pass filter and reduce the gain at high frequencies. The input resistor, R_{in} should be small compared to the feedback resistor, R_f in order to have a negligible effect on the desired signal, while a bias compensating resistor may also be used on the noninverting input.

EFFECTS OF INPUT NOISE ON COMPARATOR OPERATION

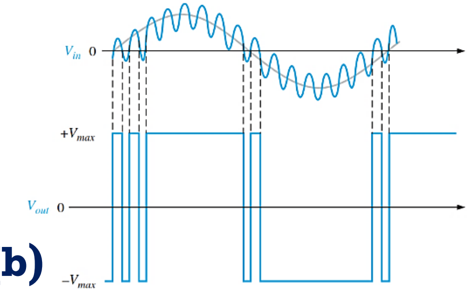
- In many practical situations, noise (unwanted voltage fluctuations) appears on the input line. This noise voltage becomes superimposed on the input voltage and can cause a comparator to erratically switch output states as shown in Figure for the case of a sine wave.
- In order to understand the potential effects of noise voltage, consider a low-frequency sinusoidal voltage applied to the noninverting (+) input of an op-amp comparator used as a zero-level detector, as shown in Figure (a).
- Figure (b) shows the input sine wave plus noise and the resulting output. When the sine wave approaches 0, the fluctuations due to noise may cause the total input to vary above and below 0 several times, thus producing an erratic output voltage.



Sine wave with superimposed



(a)



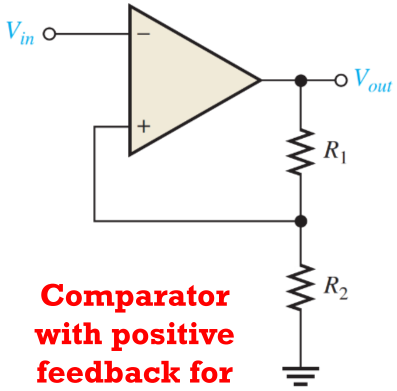
(b)

Effects of noise on comparator circuit

REDUCING NOISE EFFECTS WITH HYSTERESIS

Cont….

- This unstable condition occurs when the input voltage hovers around the reference voltage, and any small noise fluctuations cause the comparator to switch first one way and then the other.
- In order to make the comparator less sensitive to noise, a technique incorporating positive feedback, called **hysteresis,** can be used.
- Basically, hysteresis means that there is a higher reference level when the input voltage goes from a lower to higher value than when it goes from a higher to a lower value.
- A good example of hysteresis is a common household thermostat that turns the furnace on at one temperature and off at another.
- This two-level hysteresis is established with a positive feedback arrangement, as shown in Figure.



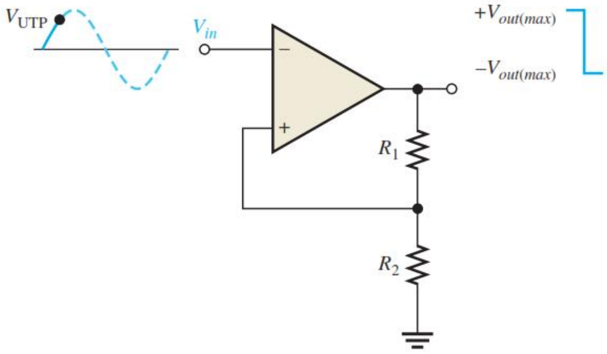
Comparator with positive feedback for hysteresis

REDUCING NOISE EFFECTS WITH HYSTERESIS

Cont….

- The two reference levels are referred to as the upper trigger point (UTP) and the lower trigger point (LTP).
- Notice that the noninverting (+) input is connected to a resistive voltage divider such that a portion of the output voltage is fed back to the input. The input signal is applied to the inverting (−) input in this case.
- Assume that the output voltage is at its positive maximum, $+V_{out(max)}$.
- The voltage fed-back to the noninverting input is V_{UTP} and is expressed as;

$$V_{\mathrm{UTP}} = \frac{R_2}{R_1 + R_2}(+V_{out(max)})$$



(a) When the output is at the maximum positive voltage and the input exceeds UTP, the output switches to the maximum negative voltage

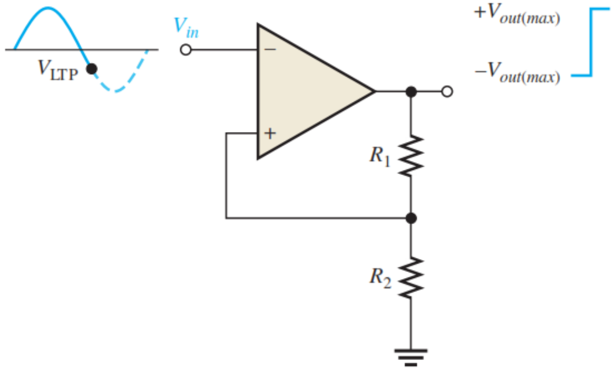
REDUCING NOISE EFFECTS WITH HYSTERESIS

Cont….

- When V_{in} exceeds V_{UTP}, the output voltage drops to its negative maximum, $-V_{out(max)}$, as shown in Figure (a).
- Now the voltage fed back to the noninverting input is V_{LTP} and is expressed as

$$V_{\mathrm{LTP}} = \frac{R_2}{R_1 + R_2}(-V_{out(max)})$$

- The input voltage must now fall below V_{LTP}, as shown in Figure (b), before the device will switch from the maximum negative voltage back to the maximum positive voltage.



(b) When the output is at the maximum negative voltage and the input goes below LTP, the output switches back to the maximum positive voltage.

REDUCING NOISE EFFECTS WITH HYSTERESIS

Cont….

- ☐ This means that a small amount of noise voltage has no effect on the output, as illustrated by Figure (c).
- ☐ A comparator with built-in hysteresis is sometimes known as a **Schmitt trigger.** The amount of hysteresis is defined by the difference of the two trigger levels.

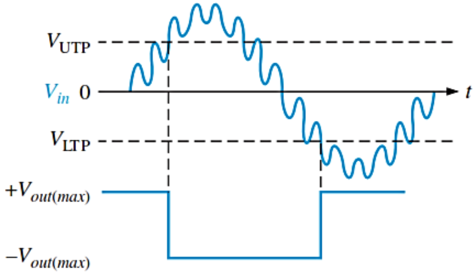
$$V_{HYS} = V_{UTP} - V_{LTP}$$

Example: Determine the upper and lower trigger points for the comparator circuit in Figure. Assume that $+V_{out(max)} = +5$ V and $-V_{out(max)} = -5$V.

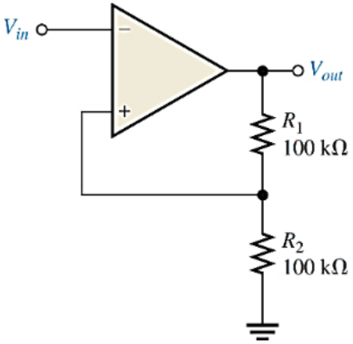
Solution:

$$V_{UTP} = \frac{R_2}{R_1 + R_2}(+V_{out(max)}) = 0.5(5\text{ V}) = \mathbf{+2.5\text{ V}}$$

$$V_{LTP} = \frac{R_2}{R_1 + R_2}(-V_{out(max)}) = 0.5(-5\text{ V}) = \mathbf{-2.5\text{ V}}$$



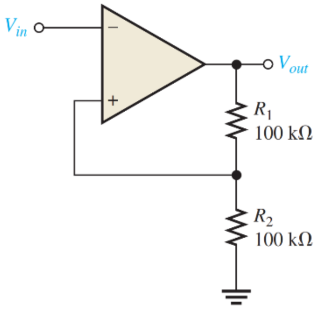
(c) Device triggers only once when UTP or LTP is reached; thus, there is immunity to noise that is riding on the input signal.



REDUCING NOISE EFFECTS WITH HYSTERESIS

Related Problem:

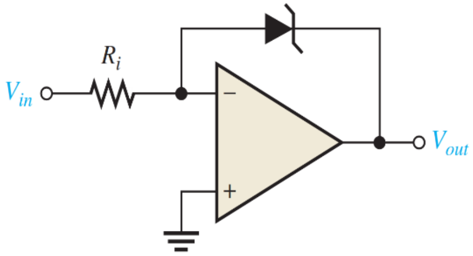
Determine the upper and lower trigger points in Figure for $R_1 = 68$ kΩ and $R_2 = 82$ kΩ. Also assume the maximum output voltage levels are now ±7 V.



REDUCING NOISE EFFECTS WITH OUTPUT BOUNDING

Cont.…

- In some applications, it is necessary to limit the output voltage levels of a comparator to a value less than that provided by the saturated op-amp.
- A single zener diode can be used, as shown in Figure, to limit the output voltage to the zener voltage in one direction and to the forward diode voltage drop in the other.
- This process of limiting the output range is called bounding.

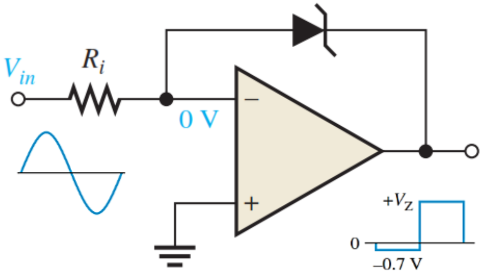


Comparator with output bounding

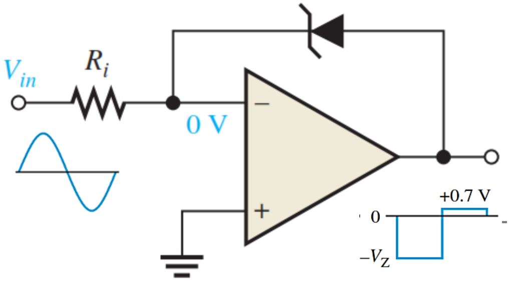
REDUCING NOISE EFFECTS WITH OUTPUT BOUNDING

Operation of a single bounded comparator:

- Since the anode of the zener is connected to the inverting (–) input, it is at virtual ground (0 V).
- Therefore, when the output voltage reaches a positive value equal to the zener voltage, it limits at that value, as illustrated in Figure (a).
- When the output switches negative, the zener acts as a regular diode and becomes forward-biased at 0.7 V, limiting the negative output voltage to this value, as shown in Figure (b).
- Turning the zener around limits the output voltage in the opposite direction.



(a) Bounded at a positive value

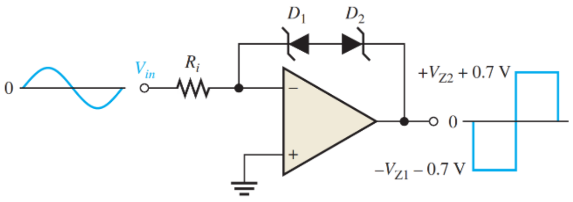


(b) Bounded at a negative value

REDUCING NOISE EFFECTS WITH DOUBLE-BOUNDED COMPARATOR

Cont….

- Two zener diodes arranged as in Figure, limit the output voltage to the zener voltage plus the forward voltage drop (0.7 V) of the forward-biased zener, both positively and negatively, as shown in Figure.

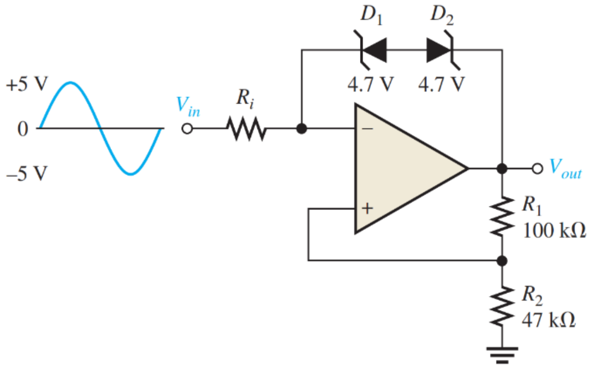


Double-Bounded Comparator

Example: Determine the output voltage waveform for Figure.

Solution:

- This comparator has both hysteresis and zener bounding. The voltage across D_1 and D_2 in either direction is 4.7 V + 0.7 V = 5.4 V.
- This is because one zener is always forward-biased



REDUCING NOISE EFFECTS WITH DOUBLE-BOUNDED COMPARATOR

Cont….

- The voltage at the (–) inverting op-amp input is V_{out} ±5.4 V.
- Since the differential voltage is negligible, the voltage at the noninverting (+) op-amp input is also approximately V_{out} ±5.4 V.

$$V_{R1} = V_{out} - (V_{out} \pm 5.4\text{ V}) = \pm 5.4\text{ V}$$

$$I_{R1} = \frac{V_{R1}}{R_1} = \frac{\pm 5.4\text{ V}}{100\text{ k}\Omega} = \pm 54\ \mu\text{A}$$

- Since the noninverting input current is negligible, therefore

$$I_{R2} = I_{R1} = \pm 54\ \mu\text{A}$$

$$V_{R2} = R_2 I_{R2} = (47\text{ k}\Omega)(\pm 54\ \mu\text{A}) = \pm 2.54\text{ V}$$

$$V_{out} = V_{R1} + V_{R2} = \pm 5.4\text{ V} \pm 2.54\text{ V} = \pm 7.94\text{ V}$$

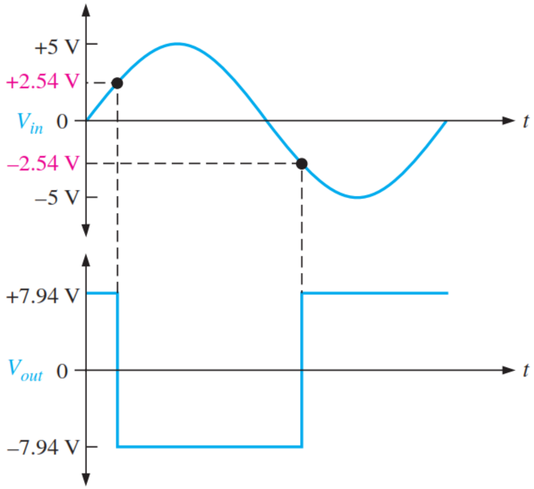
- The upper trigger point (UTP) and the lower trigger point (LTP) are as follows:

$$V_{\text{UTP}} = \left(\frac{R_2}{R_1 + R_2}\right)(+V_{out}) = \left(\frac{47\text{ k}\Omega}{147\text{ k}\Omega}\right)(+7.94\text{ V}) = +2.54\text{ V}$$

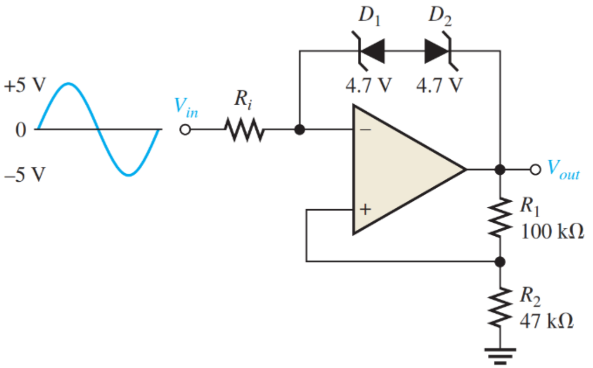
$$V_{\text{LTP}} = \left(\frac{R_2}{R_1 + R_2}\right)(-V_{out}) = \left(\frac{47\text{ k}\Omega}{147\text{ k}\Omega}\right)(-7.94\text{ V}) = -2.54\text{ V}$$

- The output waveform for the given input voltage is shown in Figure.

REDUCING NOISE EFFECTS WITH DOUBLE-BOUNDED COMPARATOR



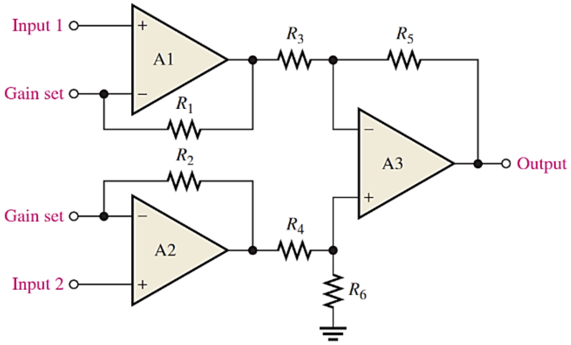
Related Problem: Determine the upper and lower trigger points for Figure. if R_1= 150 kΩ, R_2 = 68 kΩ, and the zener diodes are 3.3 V devices.



INSTRUMENTATION AMPLIFIERS

Cont….

- An instrumentation amplifier is a differential voltage-gain device that amplifies the difference between the voltages existing at its two input terminals.
- The main purpose of an instrumentation amplifier is to amplify small signals that may be riding on large common mode voltages.
- The key characteristics are high input impedance, high common-mode rejection, low output offset, and low output impedance. The basic instrumentation amplifier is an integrated circuit that internally has three operational amplifiers and several resistors as shown in Figure.
- Op-amps A1 and A2 are noninverting configurations that provide high input impedance and voltage gain. Op-amp A3 is used as a unity-gain differential amplifier



Basic instrumentation amplifier using three op-amps.

INSTRUMENTATION AMPLIFIERS

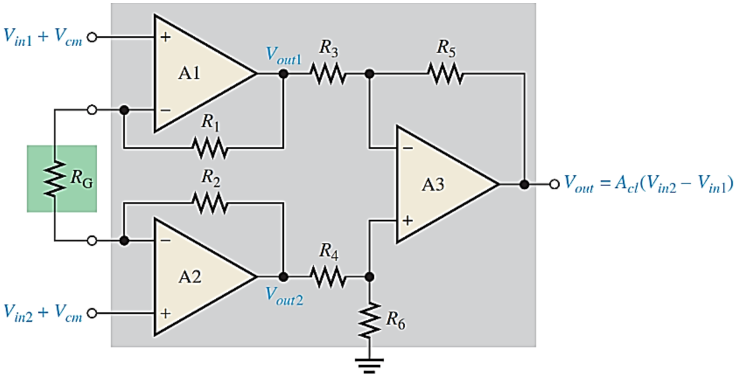
Cont….

- The voltage gain of an instrumentation amplifier is usually set with an external resistor, R_G as shown in Figure.
- Op-amp A1 receives the differential input signal V_{in1} on its noninverting (+) input and amplifies this signal with a voltage gain of;
- Op-amp A1 also has V_{in2} as an input signal to its inverting (–) input through op-amp A2 and the path formed by R_2 and R_G.

$$A_v = 1 + \frac{R_1}{R_G}$$

- The input signal V_{in2} is amplified by op-amp A1 with a voltage gain of;

$$A_v = \frac{R_1}{R_G}$$



Basic instrumentation amplifier with an external gain-setting resistor R_G.Differential and common-mode signals are indicated.

INSTRUMENTATION AMPLIFIERS

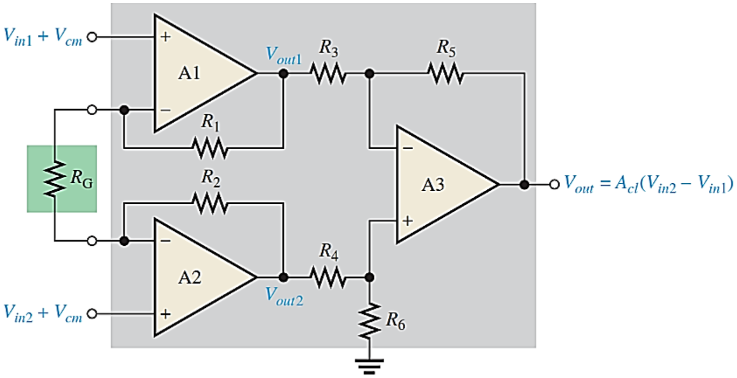
Cont….

The overall **CLOSED-LOOP** gain of the instrumentation amplifier is;

$$A_{cl} = 1 + \frac{2R}{R_G}$$

- where $R_1 = R_2 = R$.
- The above Equation shows that the gain of the instrumentation amplifier can be set by the value of the external resistor R_G when R_1 and R_2 have a known fixed value.
- The external gain-setting resistor R_G can be calculated for a desired voltage gain by applying Equation.

$$R_G = \frac{2R}{A_{cl} - 1}$$



Basic instrumentation amplifier with an external gain-setting resistor R_G .Differential and common-mode signals are indicated.

INSTRUMENTATION AMPLIFIERS

Cont….

Example:

Determine the value of the external gain-setting resistor R_G for a certain IC instrumentation amplifier with $R_1 = R_2 = 25\ k\Omega$. The closed-loop voltage gain is to be 500.

Solution:

$$R_G = \frac{2R}{A_{cl} - 1} = \frac{50\ \text{k}\Omega}{500 - 1} \cong \mathbf{100\ \Omega}$$

Related Problem:

What value of external gain-setting resistor is required for an instrumentation

END OF LECTURE # 04

Thank you !!!